Supernova Neutrinos – The Spectacular Display of Nature

A.B. Balantekin,
LBNL Physics Workhop,
Santa Fe April 25-26

SN 1987A remnant

How do you cook elements around us?

How do you cook elements around us?

Pop III stars
(very big and very
metal poor)

How do you cook elements around us?

How do you cook elements around us?

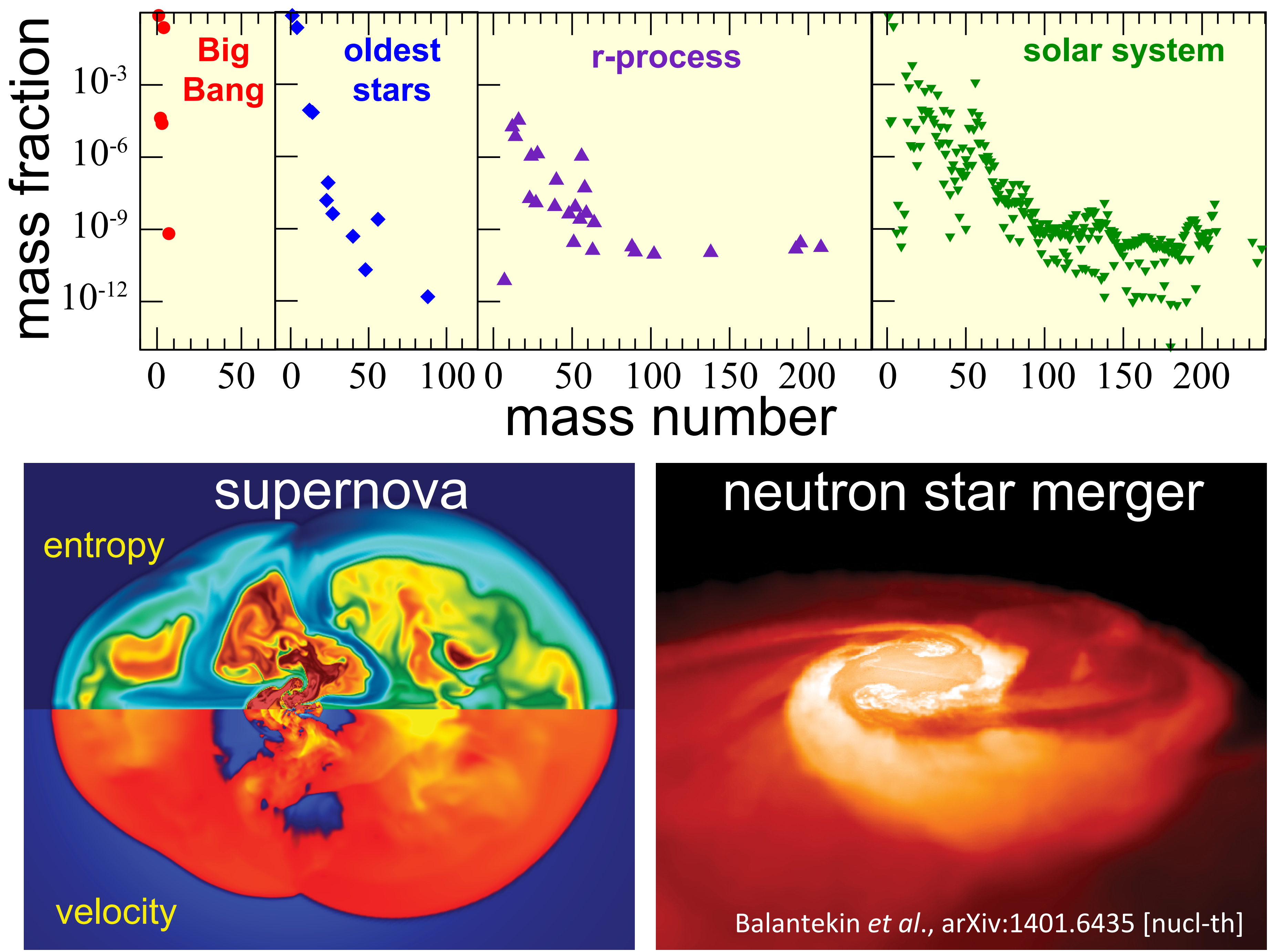
How do you cook elements around us?

How do you cook elements around us?

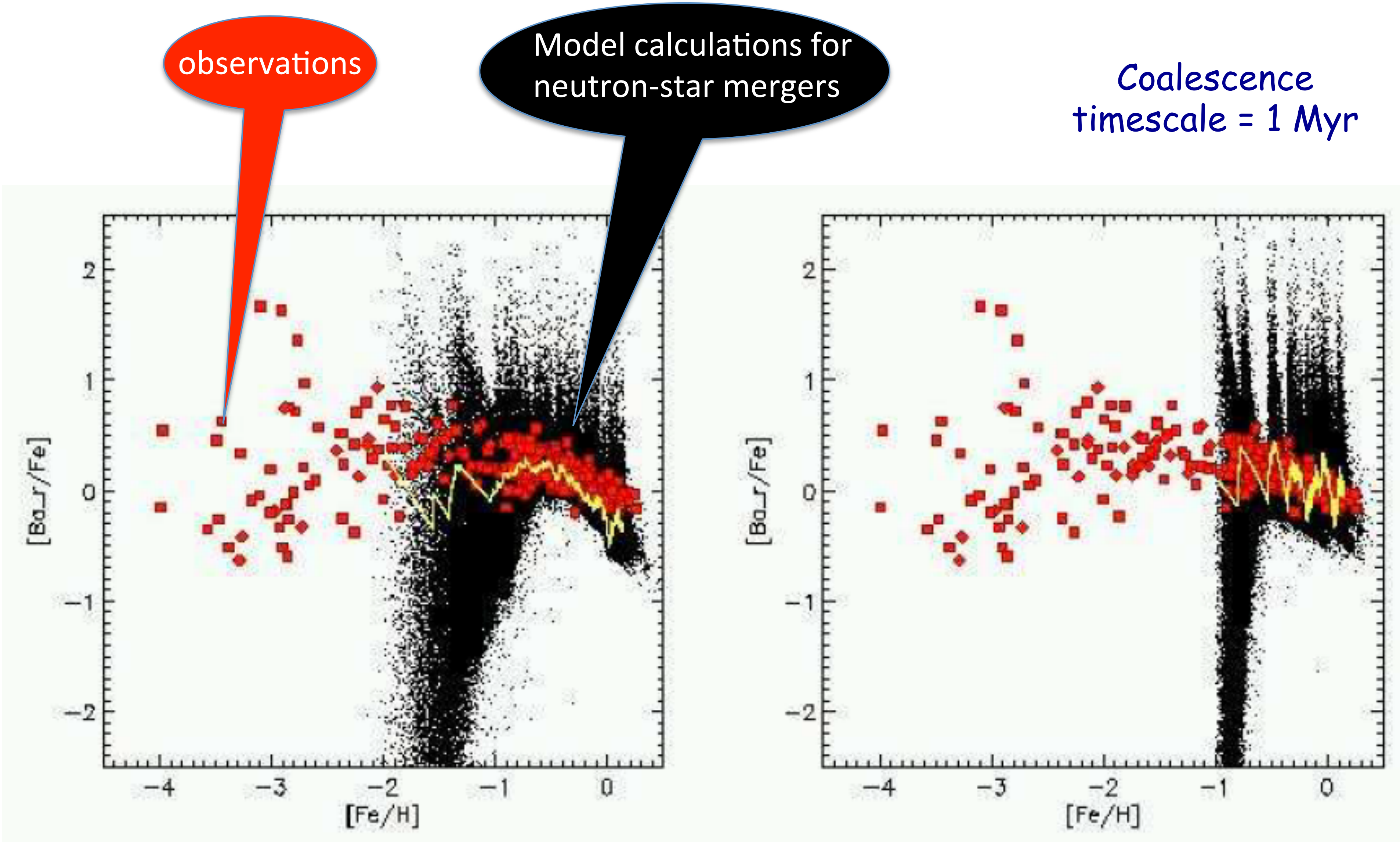
Some go supernova, producing U, Eu, Th… via the r-process

Pop II stars (metal poor)

AGB stars produce Ba, La, Y,…. via the s-process



mass fraction
10-3
10-6
10-9
10-12
Big Bang
oldest stars
r-process
solar system
0
50
100
150
200
mass number
supernova
entropy
velocity
neutron star merger
Balantekin et al., arXiv:1401.6435 [nucl-th]



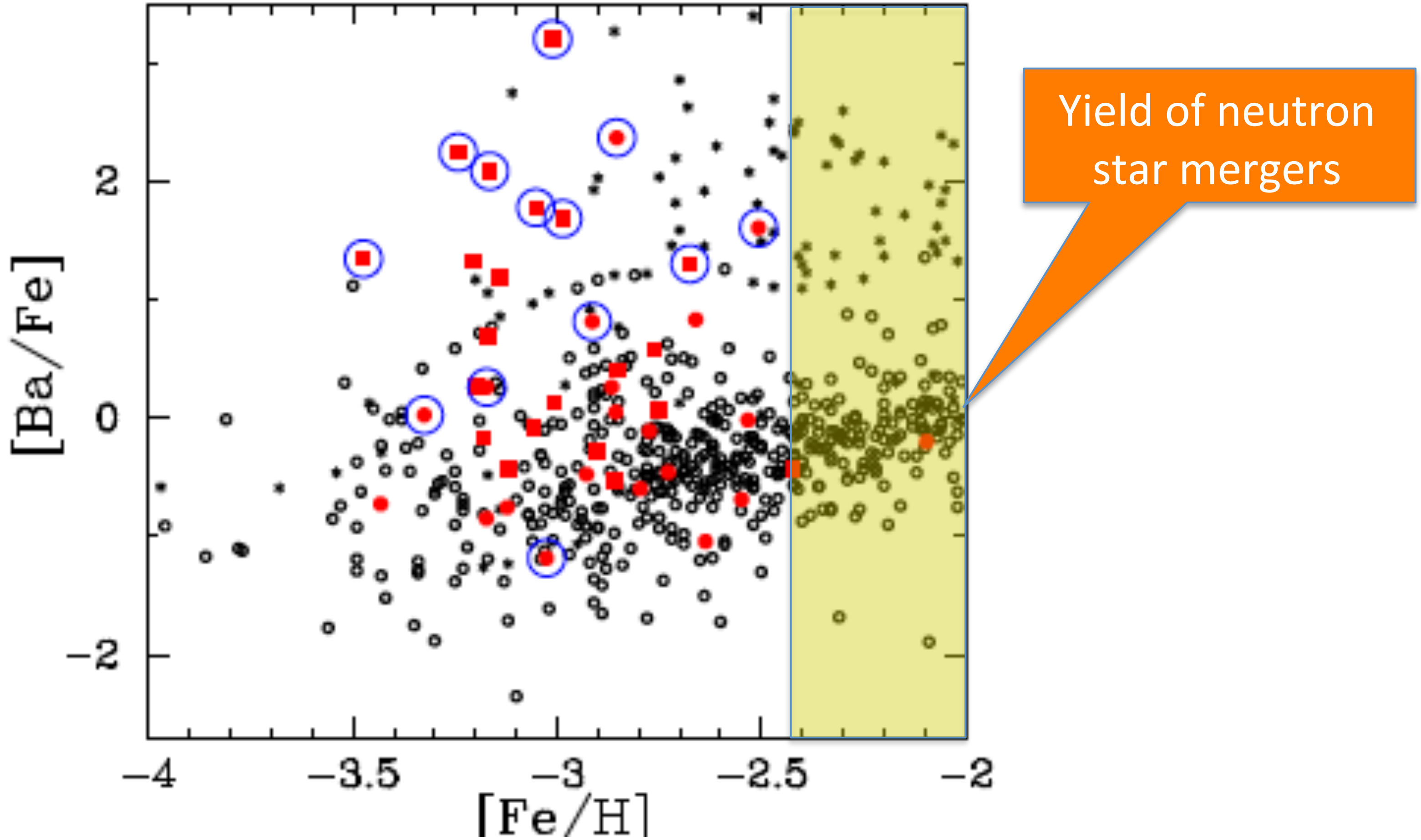
Coalescence
timescale = 1 Myr

Average merger rate = 20/Myr

Average merger rate = 2/Myr

Star formation rate?

Argast *et al.*, A&A, **416**, 997 (2003)

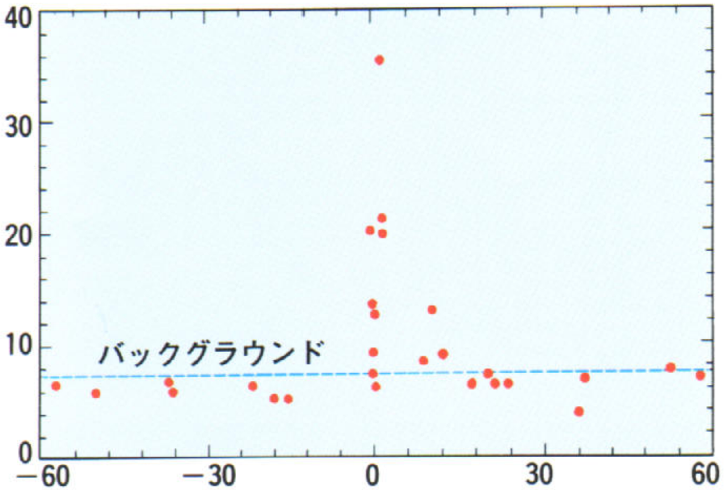


SDSS Data from Aoki *et al.*, arXiv: 1210.1946 [astro-ph.SR]

Neutrinos from core-collapse supernovae

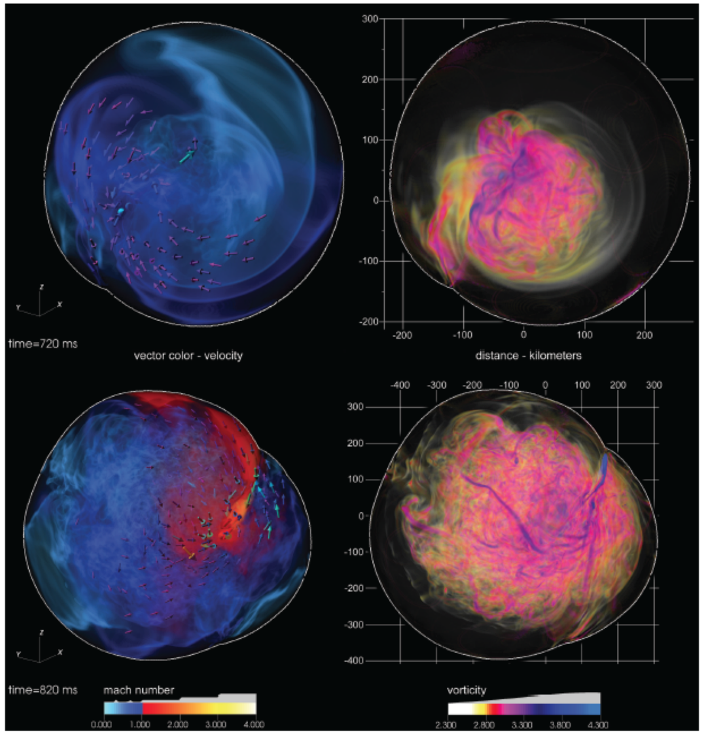
- $M_{prog} \geq 8\ M_{Sun}$
- $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
- 99% of the energy is carried away by neutrinos and antineutrinos with

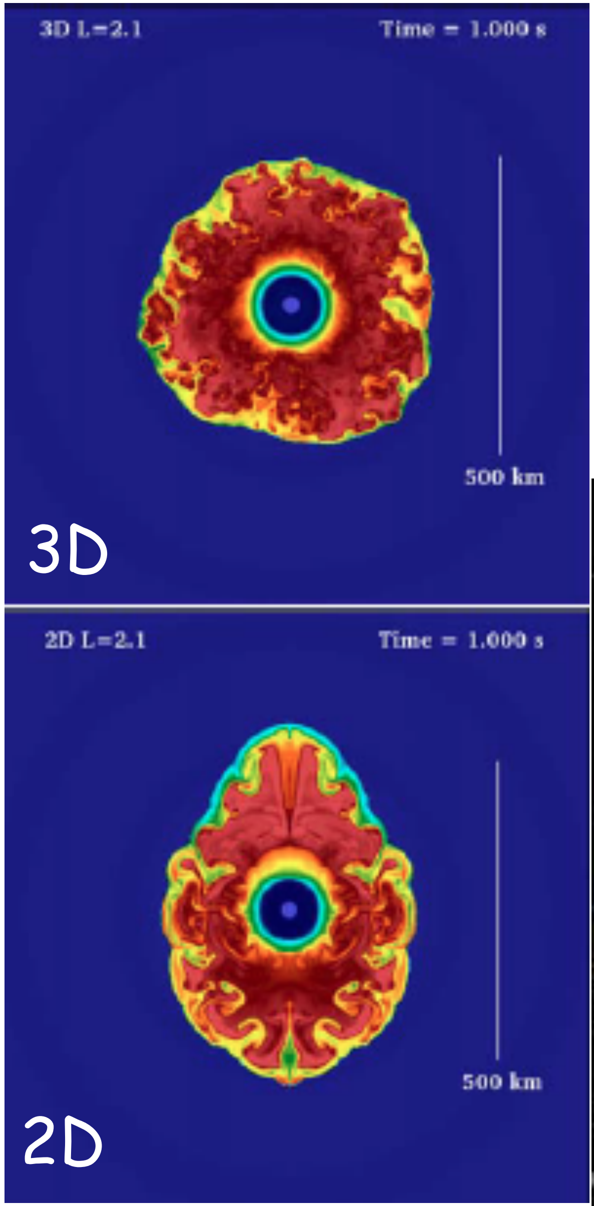
  $10 \leq E_\nu \leq 30$ MeV
- ~ 10^{58} Neutrinos!



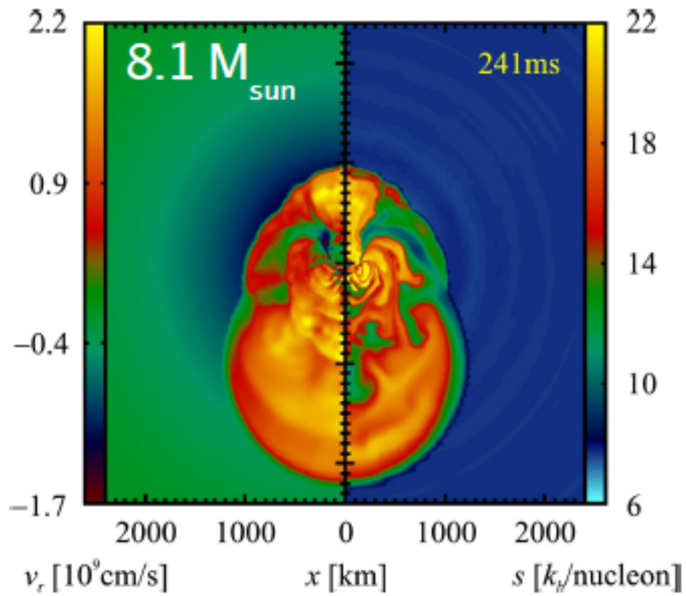
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.

ORNL/UT

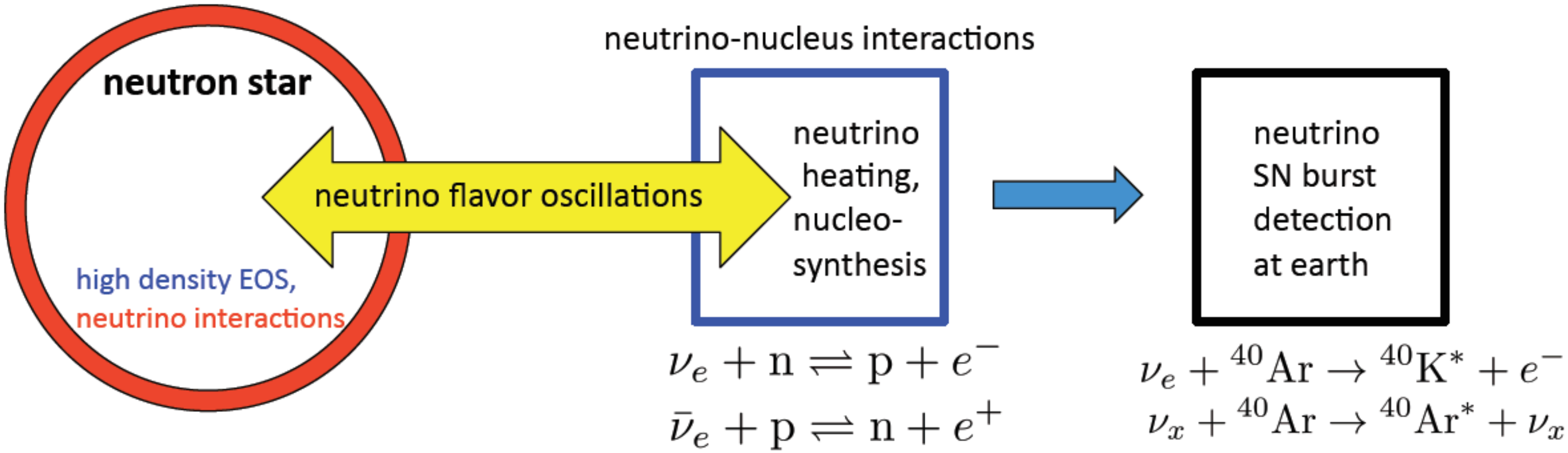




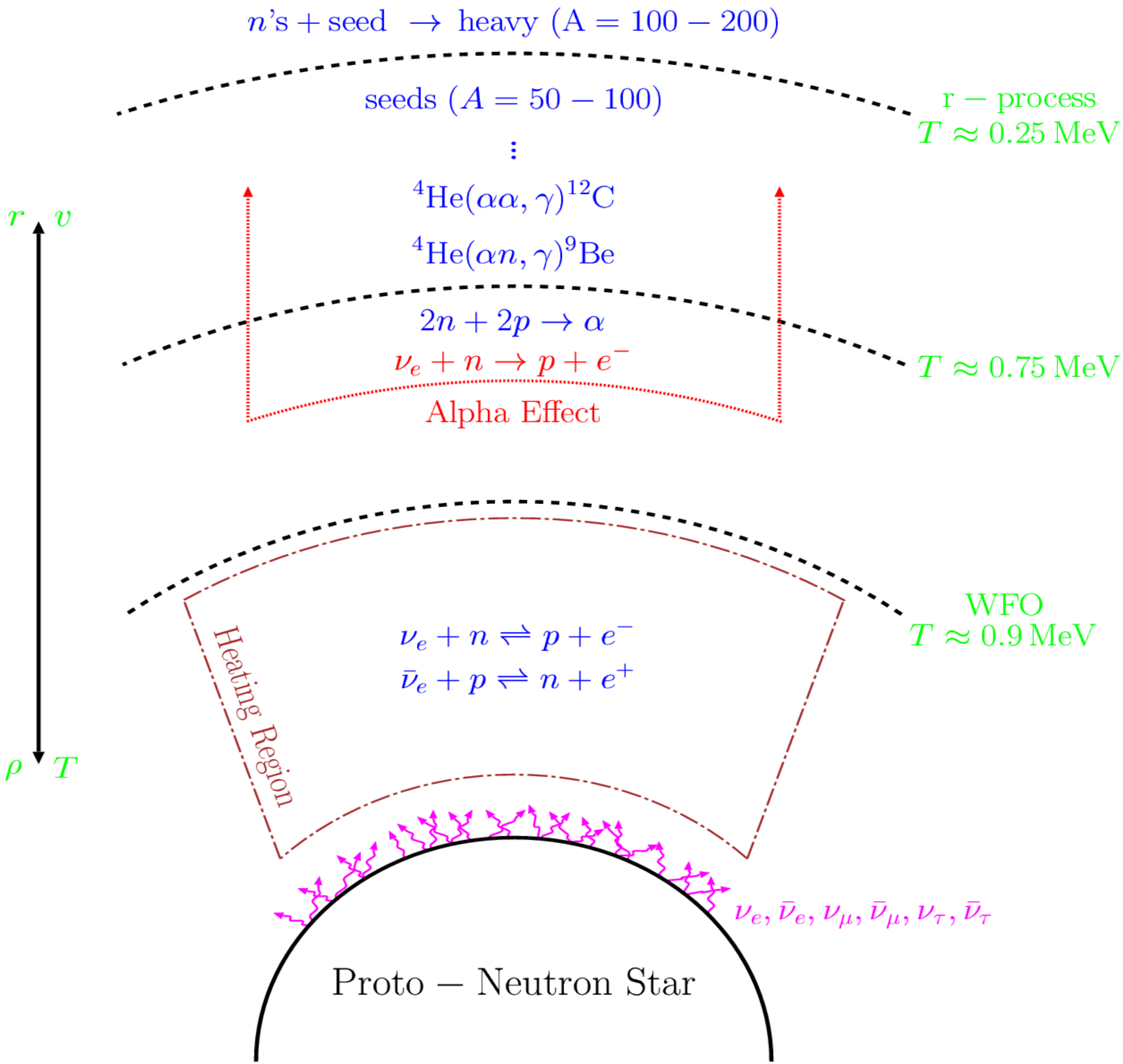
Princeton

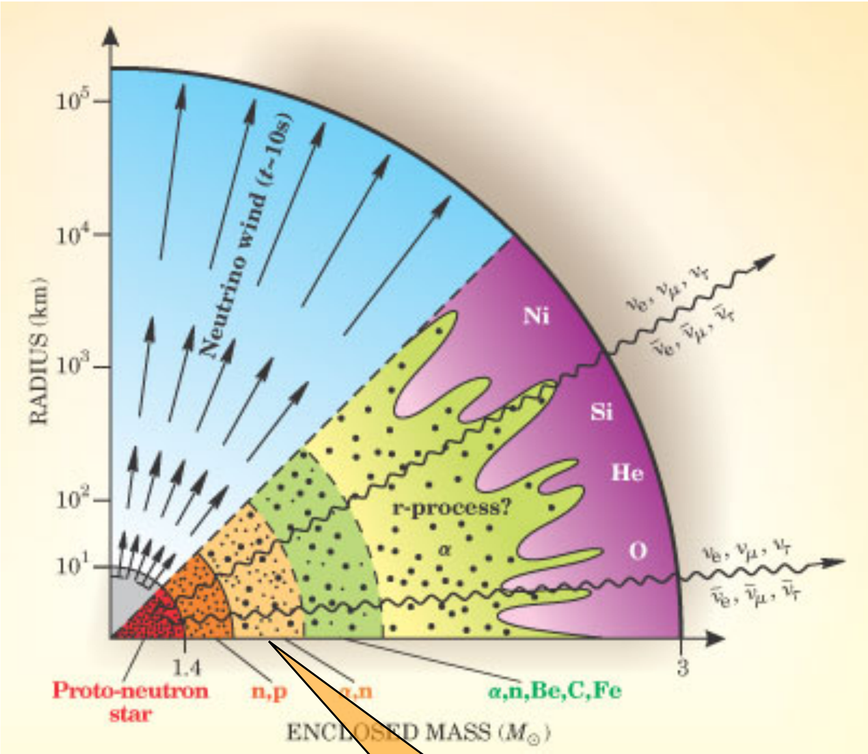


Munich

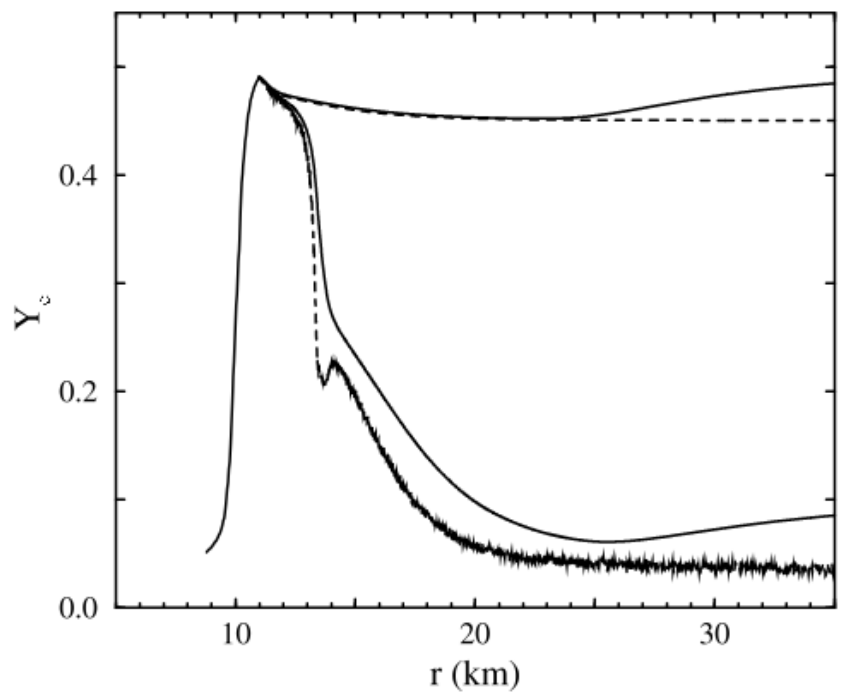


Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013).


n's + seed $\rightarrow$ heavy (A = 100 − 200)
seeds ($A = 50 - 100$)
⋮
^{4}He$(\alpha\alpha,\gamma)^{12}$C
^{4}He$(\alpha n,\gamma)^{9}$Be
$2n + 2p \rightarrow \alpha$
$\nu_e + n \rightarrow p + e^-$
Alpha Effect
r − process
$T \approx 0.25$ MeV
$T \approx 0.75$ MeV
WFO
$T \approx 0.9$ MeV
r
v
ρ
T
$\nu_e + n \rightleftharpoons p + e^-$
$\bar{\nu}_e + p \rightleftharpoons n + e^+$
Heating Region
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
Proto − Neutron Star

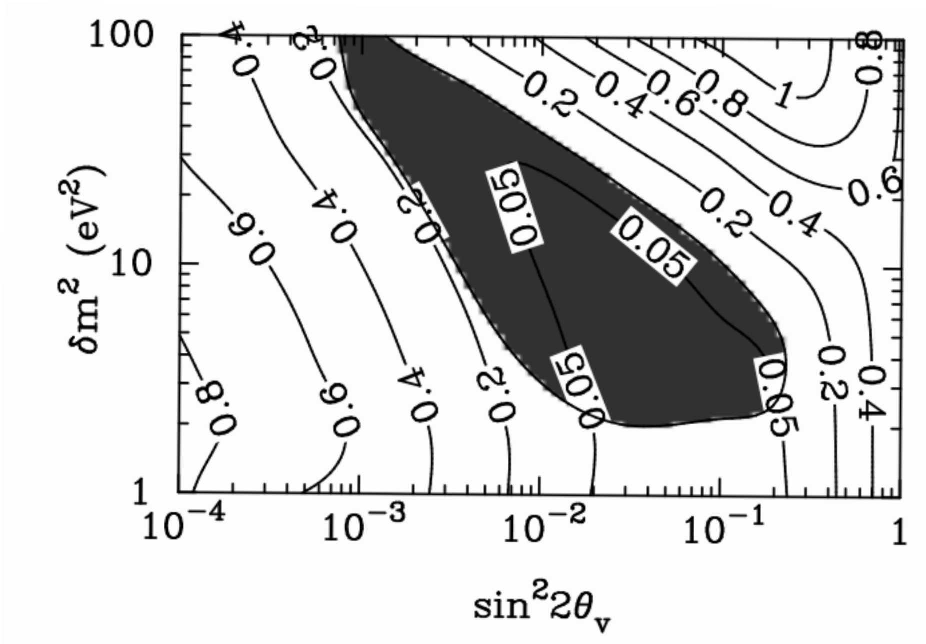


Alpha effect



Active-sterile mixing

McLaughlin, Fetter, Balantekin, Fuller, Astropart. Phys., 18, 433 (2003)



The MSW Effect

In vacuum: $E^2 = \mathbf{p}^2 + m^2$

In matter:

$(E - V)^2 = (\mathbf{p} - \mathbf{A})^2 + m^2$

$\Rightarrow E^2 = \mathbf{p}^2 + m^2_{\text{eff}}$

V $\propto$ background density

$\mathbf{A} \propto \mathbf{J}_{\text{background}}$ (currents) or

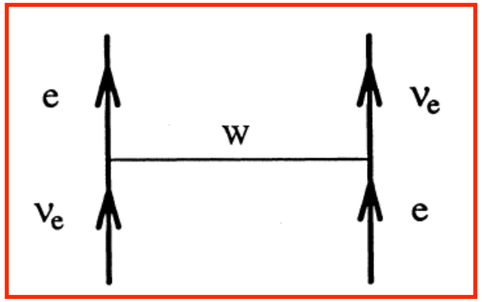
$\mathbf{A} \propto \mathbf{S}_{\text{background}}$ (spin)

In the limit of static, charge-neutral, and unpolarized background

V$\propto N_e$ and $\mathbf{A} = 0$

$\Rightarrow m^2_{\text{eff}} = m^2 + 2EV + \mathcal{O}(V^2)$

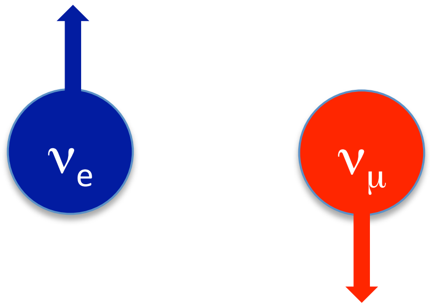
The potential is provided by the coherent forward scattering of ν_e's off the electrons in dense matter



There is a similar term with Z-exchange. But since it is the same for all neutrino flavors *at the tree level*, it does not contribute to phase differences *unless* we invoke sterile neutrinos.

Note the fine print!

Neutrino flavor isospin



$$\hat{J}_+ = a_e^\dagger a_\mu \qquad \hat{J}_- = a_\mu^\dagger a_e$$

$$\hat{J}_0 = \frac{1}{2}\left(a_e^\dagger a_e - a_\mu^\dagger a_\mu\right)$$

These operators can be written in either mass or flavor basis

Free neutrinos (only mixing)

$$\hat{H} = \frac{m_1^2}{2E} a_1^\dagger a_1 + \frac{m_2^2}{2E} a_2^\dagger a_2 + (\cdot\cdot)\hat{1}$$

$$= \frac{\delta m^2}{4E}\cos 2\theta\left(a_\mu^\dagger a_\mu - a_e^\dagger a_e\right) + \frac{\delta m^2}{4E}\sin 2\theta\left(a_e^\dagger a_\mu + a_\mu^\dagger a_e\right) + (\cdot\cdot)'\,\hat{1}$$

Interacting with background electrons

$$\hat{H} = \left[\frac{\delta m^2}{4E}\cos 2\theta - \frac{1}{\sqrt{2}} G_F N_e\right]\left(a_\mu^\dagger a_\mu - a_e^\dagger a_e\right) + \frac{\delta m^2}{4E}\sin 2\theta\left(a_e^\dagger a_\mu + a_\mu^\dagger a_e\right) + (\cdot\cdot)''\,\hat{1}$$

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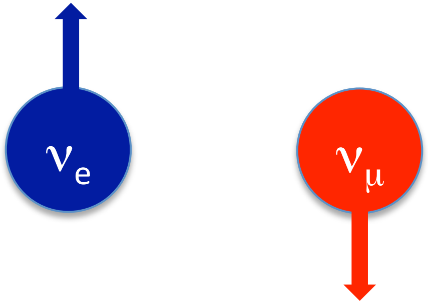

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Free neutrinos (only mixing)

$$\begin{aligned}\hat{H} &= \frac{m_1^2}{2E} a_1^\dagger a_1 + \frac{m_2^2}{2E} a_2^\dagger a_2 + (\cdot\cdot)\hat{1} \\ &= \frac{\delta m^2}{4E}\cos 2\theta\left(-2\hat{J}_0\right) + \frac{\delta m^2}{4E}\sin 2\theta\left(\hat{J}_+ + \hat{J}_-\right) + (\cdot\cdot)'\,\hat{1}\end{aligned}$$

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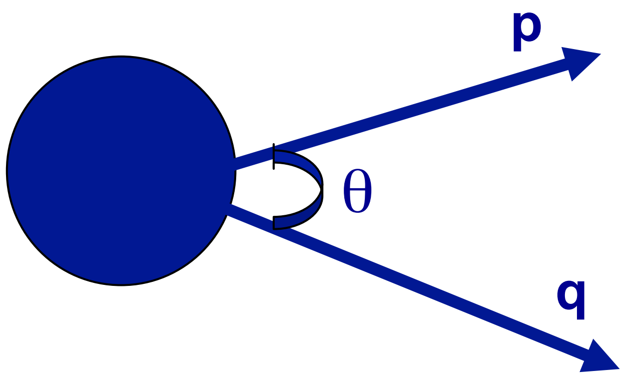
Neutrino-Neutrino Interactions

Smirnov, Fuller and Qian, Pantaleone, McKellar, Friedland, Lunardini, Raffelt, Balantekin, Kajino, Pehlivan …

$$\hat{H}_{\nu\nu} = \frac{\sqrt{2}G_F}{V} \int dp\, dq \left(1 - \cos\theta_{pq}\right) \vec{\mathbf{J}}_p \cdot \vec{\mathbf{J}}_q$$



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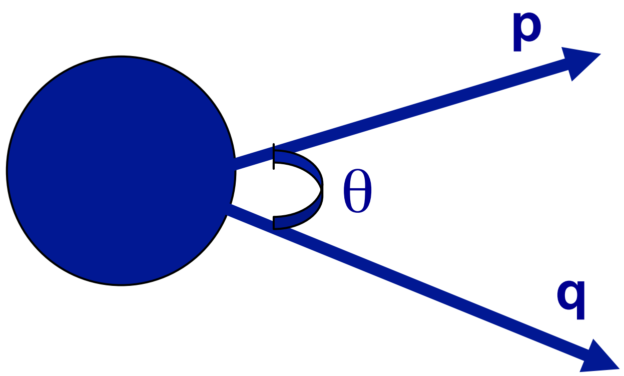


This term makes the physics of a neutrino gas in a core-collapse supernova a genuine many-body problem

$$\hat{H} = \int dp\left(\frac{\delta m^2}{2E}\vec{\mathbf{B}}\cdot\vec{\mathbf{J}}_p - \sqrt{2}G_F N_e \mathbf{J}_p^0\right) + \frac{\sqrt{2}G_F}{V}\int dp\,dq\left(1-\cos\theta_{pq}\right)\vec{\mathbf{J}}_p\cdot\vec{\mathbf{J}}_q$$

$$\vec{\mathbf{B}} = \left(\sin 2\theta,\ 0, -\cos 2\theta\right)$$

Neutrino-neutrino interactions lead to novel collective and emergent effects, such as conserved quantities and interesting features in the neutrino energy spectra (spectral "swaps" or "splits").

Many neutrino system

This is the only many-body system driven by the weak interactions:

Table: Many-body systems

Nuclei	Strong	at most $\sim$250 particles
Condensed matter	E&M	at most N_A particles
ν**'s in SN**	Weak	$\sim 10^{58}$particles

Astrophysical extremes allow us to test physics that cannot be tested elsewhere!

Including antineutrinos

$$H = H_\nu + H_{\bar{\nu}} + H_{\nu\nu} + H_{\bar{\nu}\bar{\nu}} + H_{\nu\bar{\nu}}$$

Requires introduction of a second set of SU(2) algebras!

Including three flavors

Requires introduction of SU(3) algebras.

Both extensions are straightforward, but tedious!
Balantekin and Pehlivan, J. Phys. G **34**, 1783 (2007).

The duality between $H_{\nu\nu}$ and BCS Hamiltonians

The ν-ν Hamiltonian

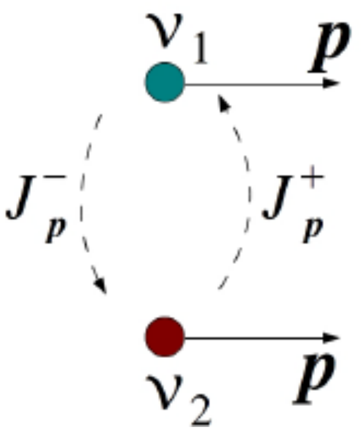
$$\hat{H} = \sum_p \frac{\delta m^2}{2p} \hat{B} \cdot \vec{J}_p + \frac{\sqrt{2} G_F}{V} \vec{J} \cdot \vec{J}$$

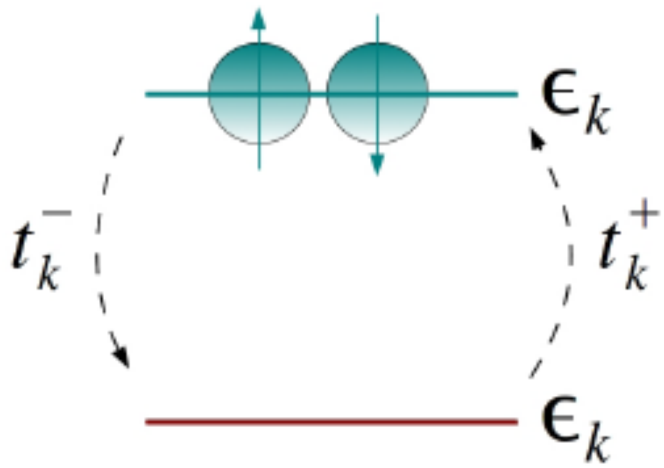
$\Longleftrightarrow$

The BCS Hamiltonian

$$\hat{H}_{\text{BCS}} = \sum_k 2\epsilon_k \hat{t}_k^0 - |G| \hat{T}^+ \hat{T}$$

Same symmetries leading to Analogous (dual) dynamics!
Pehlivan, Balantekin, Kajino, and Yoshida, Phys.Rev. D **84**, 065008 (2011)





This symmetry naturally leads to splits in the neutrino energy spectra and was used to find conserved quantities in the single-angle case.

Conserved quantities of the collective motion

$$h_p = \vec{\mathbf{B}} \cdot \vec{\mathbf{J}}_p + \frac{4\sqrt{2}G_F}{\delta m^2 V} \sum_{p \neq q} qp \frac{\vec{\mathbf{J}}_p \cdot \vec{\mathbf{J}}_q}{q - p}$$

- There is a second set of conserved quantities for antineutrinos.
- Note the presence of volume. In fact h_p/V are the conserved quantities for the neutrino densities.
- For three flavors a similar expression is written in terms of SU(3) operators.

The ν-ν Hamiltonian

$$\hat{H} = \sum_p \frac{\delta m^2}{2p} \hat{B} \cdot \vec{J}_p + \frac{\sqrt{2} G_F}{V} \vec{J} \cdot \vec{J}$$

$$\Longleftrightarrow$$

The BCS Hamiltonian

$$\hat{H}_{\mathrm{BCS}} = \sum_k 2\epsilon_k \hat{t}_k^0 - |G| \hat{T}^+ \hat{T}$$

Recall how we treat the BCS Hamiltonian. We diagonalize it in a quasiparticle basis. However that basis does not preserve particle number. We enforce the particle number conservation by introducing a Lagrange multiplier. This Lagrange multiplier turns out to be the chemical potential.

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In the many neutrino case we can do the same. The Lagrange multiplier we have to introduce to preserve the total neutrino number shows up the the final neutrino energy spectra as a "split". This is the origin of the spectral splits (or swaps) numerically observed in many calculations.

CP-violation

$$T_{23}T_{13}T_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} \psi_e \\ \tilde{\psi}_\mu \\ \tilde{\psi}_\tau \end{pmatrix} = \left[T_{13}T_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} T_{12}^\dagger T_{13}^\dagger + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & s_{23}^2 V_{\tau\mu} & -c_{23}s_{23}V_{\tau\mu} \\ 0 & -c_{23}s_{23}V_{\tau\mu} & c_{23}^2 V_{\tau\mu} \end{pmatrix} \right] \begin{pmatrix} \psi_e \\ \tilde{\psi}_\mu \\ \tilde{\psi}_\tau \end{pmatrix}$$

$$\tilde{\psi}_\mu = \cos\theta_{23}\psi_\mu - \sin\theta_{23}\psi_\tau$$

$$\tilde{\psi}_\tau = \sin\theta_{23}\psi_\mu + \cos\theta_{23}\psi_\tau$$

$$V_{e\mu} = 2\sqrt{2}G_F N_e \left[1 + O\left(\alpha \frac{m_\mu}{m_W} \right)^2 \right]$$

$$V_{\tau\mu} = -\frac{3\sqrt{2}\alpha G_F}{\pi \sin^2\theta_W}\left(\frac{m_\tau}{m_W}\right)^2 \left[\left(N_p + N_n\right)\log\frac{m_\tau}{m_W} + \left(\frac{N_p}{2} + \frac{N_n}{3}\right) \right]$$

We need to solve an evolution equation

$$i\frac{\partial}{\partial t}U = HU$$

If we ignore $V_{\tau\mu}$ it is easy to show that the CP-violating phase factorizes:

$$U(\delta) = SU(\delta = 0)S^{\dagger} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

This factorization still holds when collective oscillations are include, but breaks down if there is spin-flavor precession

This factorization implies that neither

$$P\left(\nu_e \to \nu_e\right)$$

nor

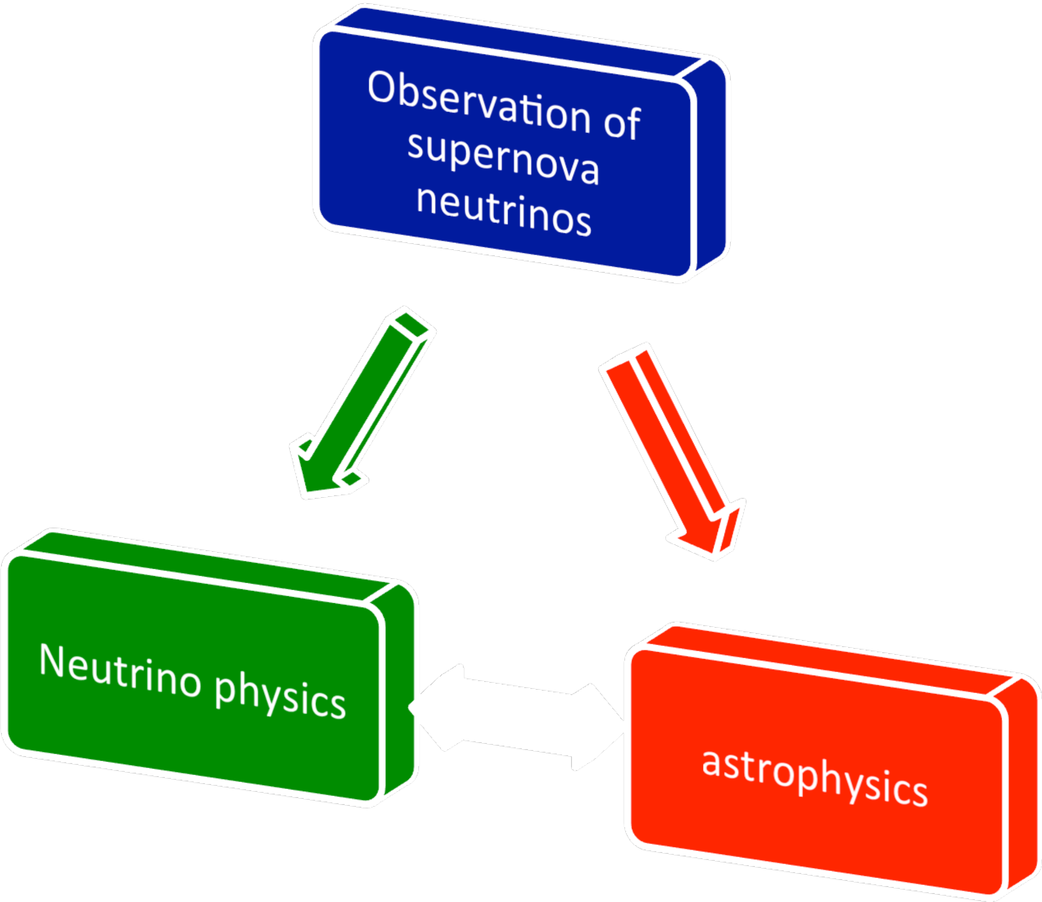
$$P\left(\nu_\mu \to \nu_e\right) + P\left(\nu_\tau \to \nu_e\right)$$

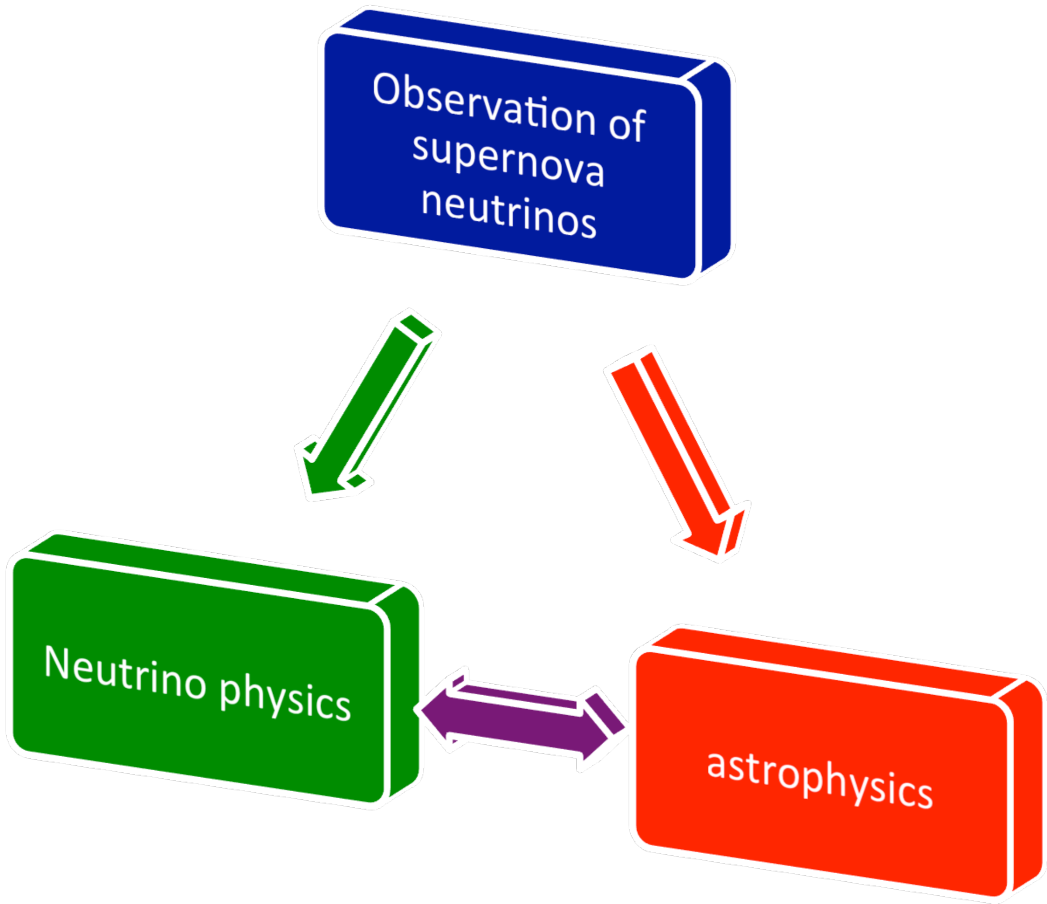
depend on the CP-violating phase δ.

If the ν_μ and ν_τ luminosities are the same at the neutrinosphere, this factorization implies that ν_e and $\bar{\nu}_e$ fluxes observed at terrestrial detectors will not be sensitive to the CP-violating phase! To see its effects you need to measure ν_μ and ν_τ luminosities separately!

If you see the effects of δ in either charged- or neutral current scattering that may mean any of the following:

- There are new neutrino interactions beyond the standard model operating either within the neutron star or during propagation.
- Standard Model loop corrections (very easy to quantify) are seen.
- There are sterile neutrino states.


Observation of supernova neutrinos
Neutrino physics
astrophysics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Many predictions of what one can observe in a core-collapse supernova are not as model-dependent as they may seem. For example, spectral swaps are a generic consequence of the neutrino number conservation. Their location may be model-dependent, but their existence is not.


Thank you very much!